ARMY RESEARCH LABORATORY

Final Report of the Rifling Profile Push Test

by Lin White and Jeff Siewert

ARL-CR-593 **June 2007**

prepared by

Arrow Tech Associates
1233 Shelburne Rd.
Suite D-8
S. Burlington, VT 05403

under contract

W911QX-05-P-0451

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14. ABSTRACT
A study was conducted to assess the engraving force and the associated resistance pressure of the M855 projectile in an M16A2 barrel section. The M855 test projectiles were tested in a 2 × 2 matrix, two different M16A2 barrel sections and two cross head rates, 1.3 and 3.6 in/s. The results of the testing are evaluated and potential ramifications are evaluated using the PRODAS software. Conclusions from the research are presented as well as recommendations for future testing.

15. SUBJECT TERMS
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Contents

List of Figures

List of Tables

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1. Introduction

The resistance force experienced by a small-caliber projectile as it transitions from the cartridge case to the barrel-forcing cone can significantly influence the interior ballistic performance of a given fixed cartridge. For this contract, the engraving force during M855 projectile transition through the forcing cone was measured for an M16A2 5.56-mm gun barrel section, and the effect on interior ballistics performance was simulated.

2. Experimental

The objective of this study was to assess the engraving force and the associated resistance pressure of the M855 projectile in an M16A2 barrel section. The M855 test projectiles were tested in a 2 × 2 matrix consisting of two different M16A2 barrel sections and two cross head rates, 1.3 in/s and 3.6 in/s. Figure 1 shows a cross section of the M855 projectile (*1*). The projectile consists of a copper gilding full metal jacket, a lead base core, and a hardened steel penetrator.

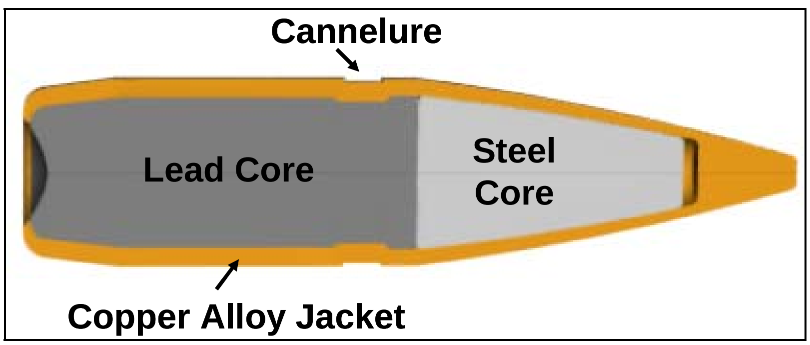

Figure 1. Cross section of 5.56-mm M855 projectile.

Two production M16A2 gun barrel assemblies were received from the U.S. Army Research Laboratory for use in this test. The barrels were star gauged by the U.S. Army Aberdeen Test Center and were found to be within technical drawing package (TDP) specifications. The barrels (PN 8448649, an assembly of the barrel 8448549 and the barrel extension 8448550) were taken to the Mechanical Engineering Department of the University of Vermont (UVM) for machining and preparation for testing. The sight, gas port, and receiver lock nut components were removed, and the bare barrel was shortened in length by the UVM Mechanical Engineering Department machine shop. Figure 2 shows a machined M16A2 barrel section used in the push test. The overall length of the barrel section was 5.5 in. The length of the barrel section chosen for push testing was chosen by elastic column buckling considerations for a reasonable punch length. A second barrel section of the M16A2 was similarly prepared for evaluation.

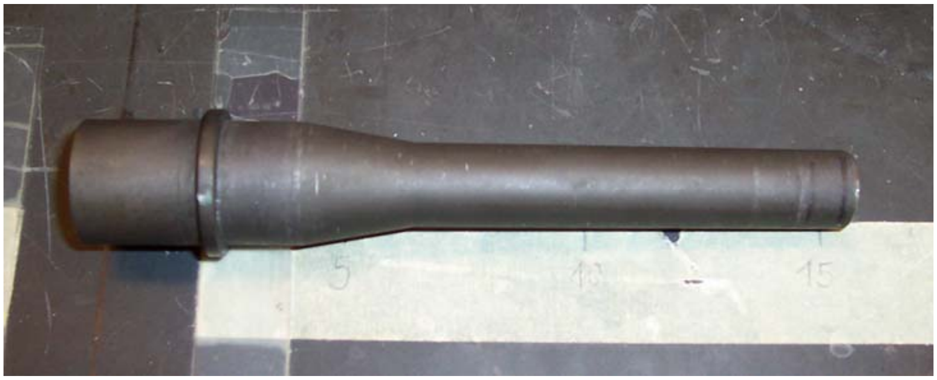

Figure 2. M16A2 barrel machined section. The units of measure are in cm.

The engraving force for each barrel was tested at the UVM Mechanical and Civil Engineering Lab. Mr. Dylan Burns, a graduate student at UVM, designed adapters to hold each barrel section for the push test. The adaptor held the cut barrel upright and attached it to actuator on the MTS testing frame. Figure 3 shows the view of the barrel adapter as well as a photograph of the test barrel section adapter fixture. The cut barrel section fits snugly into the test fixture and effectively kept the barrel held rigid throughout the testing. Figure 4 shows the M16A2 barrel section test sample being removed from the MTS adapter in between successive push tests of individual projectiles.

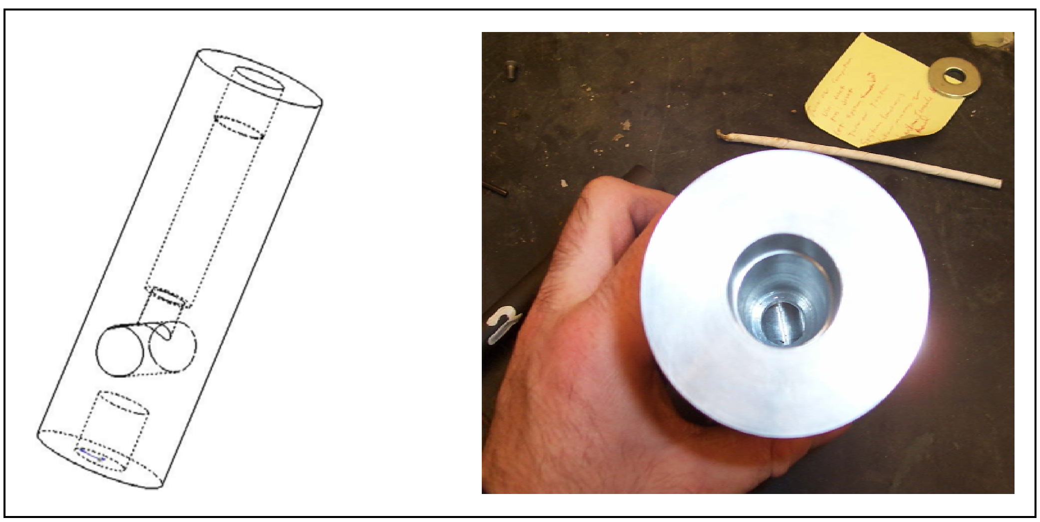

Figure 3. Drawing (left) and a top view of the barrel adapter (right).

The push test machine setup is shown in figure 5. The adapter was hard mounted to the MTS test frame while a pushing rod was compression fit into a die that fit into the frame. The push rod was a hardened steel reamer rod with a 0.2165 in diameter. The push rod was aligned so that when the test fixture with the barrel section was moved up, the rod would fit perfectly through the middle of the barrel without touching the walls. The MTS machine was calibrated using known weights and a pair of digital calipers. The MTS actuator control was programmed to

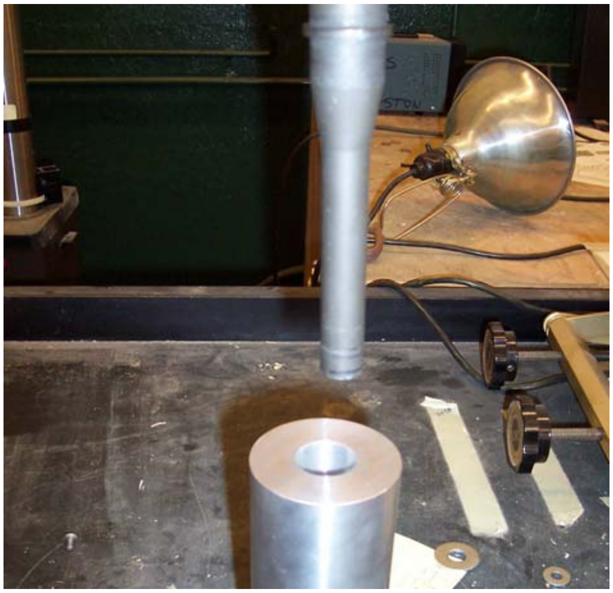

Figure 4. Intra-test change of test barrel section and MTS adapter.

Figure 5. UVM push test machine setup.

push a bullet through the barrel at a specified rate while recording the time, force and displacement. For these tests, the cross head speeds were set at 1.3 and 3.6 in/s, and the required push force (lbf) as a function of travel and time was electronically recorded. At the beginning of each test, a bullet was placed into the barrel so that the bullet made contact with the forcing cone. Then the barrel and fixture on the actuator were raised up so that the push rod was just above the

bullet. The program paused for a few seconds, and then the actuator moved up at a specified rate of 1.3 in/s, pushing the bullet through the entire length of the barrel section. After each push, the barrel section was taken out of the fixture and cleaned and then replaced with the other barrel section. The barrel sections were cleaned with “Copper Solvent IV” from Peo-Shot Products using a “Kleen Bore” universal rifle, handgun, and shot gun cleaning kit and bore brushes. This process was repeated for each bullet. This method of switching and cleaning between tests allowed the barrel sections to dissipate any heat that was generated and to ensure that there were no copper particles stuck inside the barrel. This step was meant to keep the test parameters approximately the same for each bullet. This process was repeated for the 40 bullets at each of the two testing rates. A total of 80 standard 5.56 mm production M855 projectiles were used for this test. These projectiles were procured from standard production lots from Lake City Army Ammunition Plant.

The data for every test was recorded in ascii format that was then imported and analyzed in Excel. In Excel the calibration factors were applied. The travel data was offset to the initial start point of the push test. This initial start point was considered to be when the force on the bullet was first measured. The distance was set to zero at this point and measured until the bullet was pushed completely through the barrel, which is when the force was zero again. Force vs. displacement diagrams were created for each bullet. After each test the bullet was designated a tracking number and any abnormalities in the testing procedure were noted and placed with the bullet.

Prior work done by UVM for Arrow Tech Associates in measuring the engraving force of 7.62-mm projectiles for the U.S. Army Research, Development, and Engineering Center (ARDEC) (*2*, *3*) showed a dependency of engraving force on the modulus of elasticity (*4*) of the projectile components under the contact area (*5*). The contact area was defined as the area between the projectile and the barrel lands. In the 7.62-mm projectile research, the M80 was one of the projectiles of interest, a bullet with a thin, copper-plated steel jacket and a lead core. The Barnes (*6*) copper solid projectile was also pushed in that research. The testing revealed that the Barnes projectile produced significantly higher push forces despite having a slightly smaller projectile diameter. The increase in the push force was attributed to the increase in strength of the solid copper core of the Barnes projectile compared to that of the lead-based M80 projectile.

In the case of the M855, a short length of the steel core does interface with the barrel lands through the copper alloy jacket, as shown in figure 6. As a result, compression of the jacket material above the steel core will occur and will be manifested in the results.

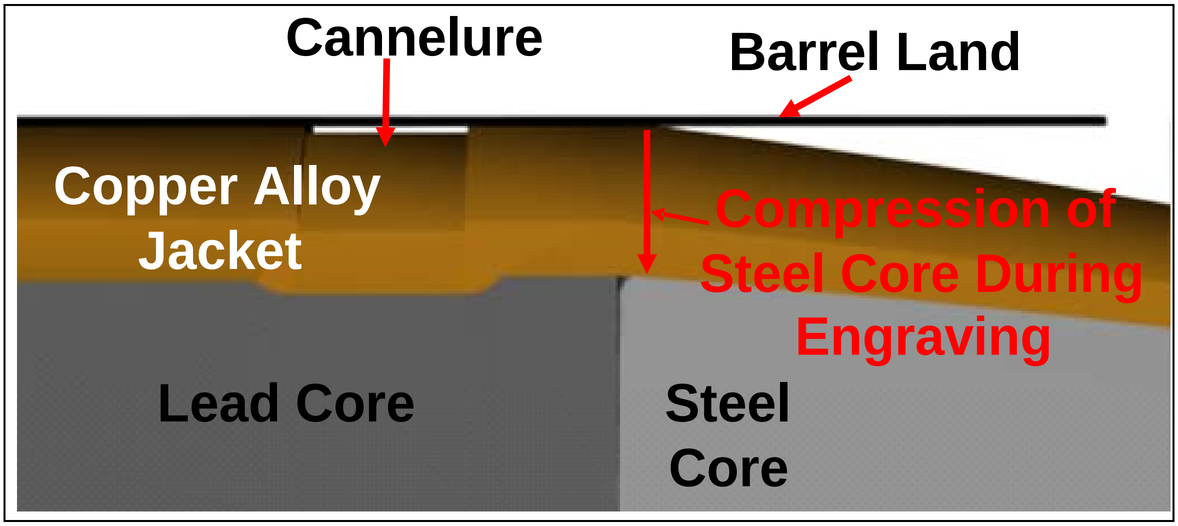

Figure 6. M855 engraving and interaction with rifling lands.

3. Results

The push force vs. travel was recorded for each barrel test section. The results are presented in figures 7–10. The data in these figures is presented as pressure vs. travel. Here, pressure is calculated as the push force divided by the bore cross-sectional areas of 0.124 in^2. In simulating interior ballistics performance, it is usually more convenient to express the projectile resistance force as an equivalent pressure, which can be subtracted from the chamber pressure to determine the net force operating on the projectile.

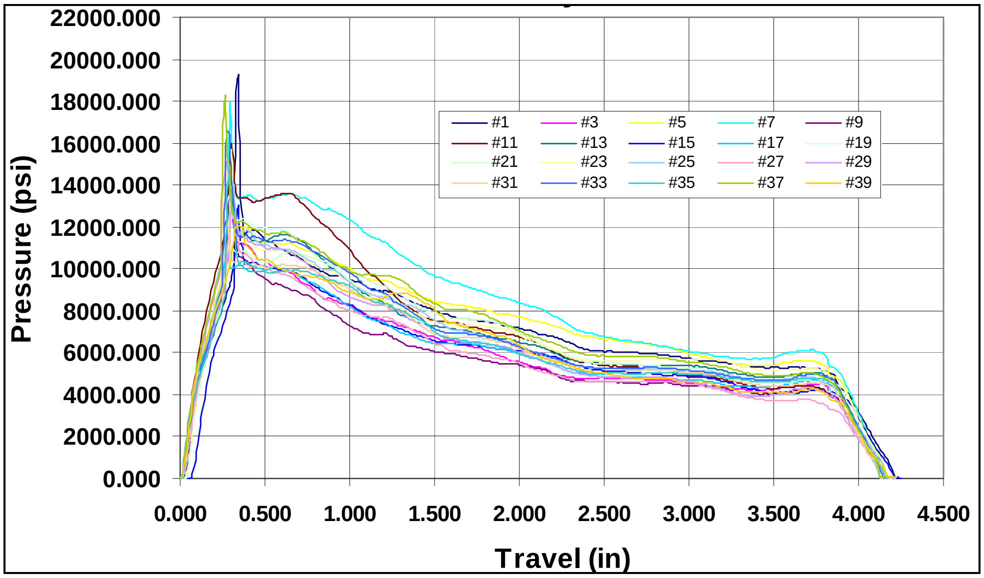

Figure 7. The push test pressure vs. travel for the "barrel #1" M16A2 barrel with a cross head speed of 1.3 in/s.

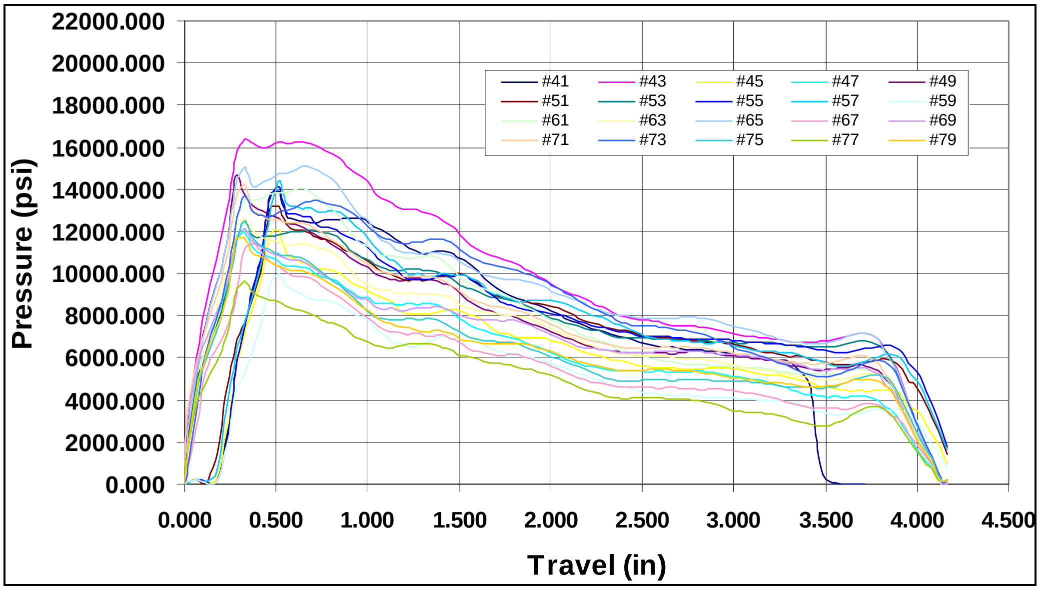

Figure 8. The push test pressure vs. travel for the “barrel #1” M16A2 barrel with a cross head speed of 3.6 in/s.

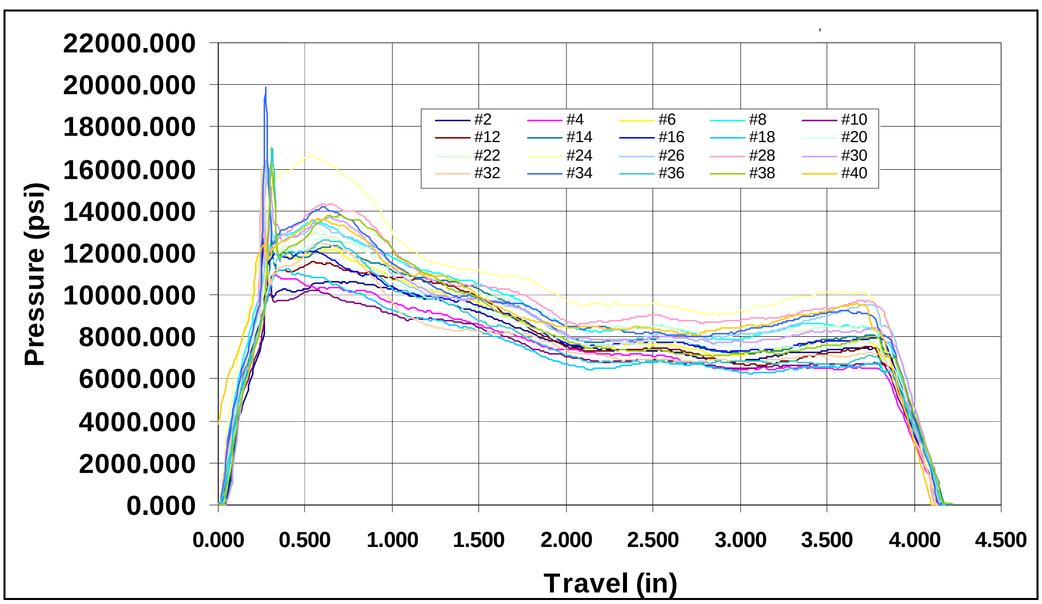

Figure 9. The push test pressure vs. travel for the “barrel #2” M16A2 barrel with a cross head speed of 1.3 in/s.

Figure 11 shows the average for the M855 in the M16A2 barrels by barrel and cross head rate. Figure 12 shows the standard deviation in engraving pressure as a function of travel for the baseline M16A2 barrel for both barrels and both test rates. The standard deviation of engraving pressure is likely responsible for a portion of the interior ballistic variability observed during normal firing and lot acceptance testing for small-caliber ammunition.

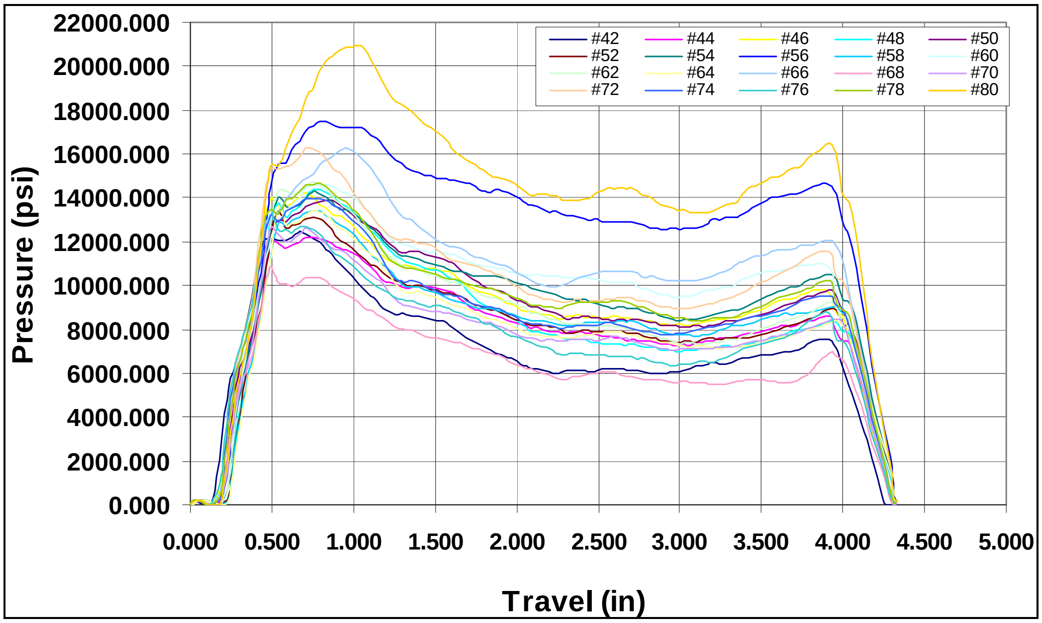

Figure 10. The push test pressure vs. travel for the "barrel #2" M16A2 barrel with a cross head speed of 3.6 in/s.

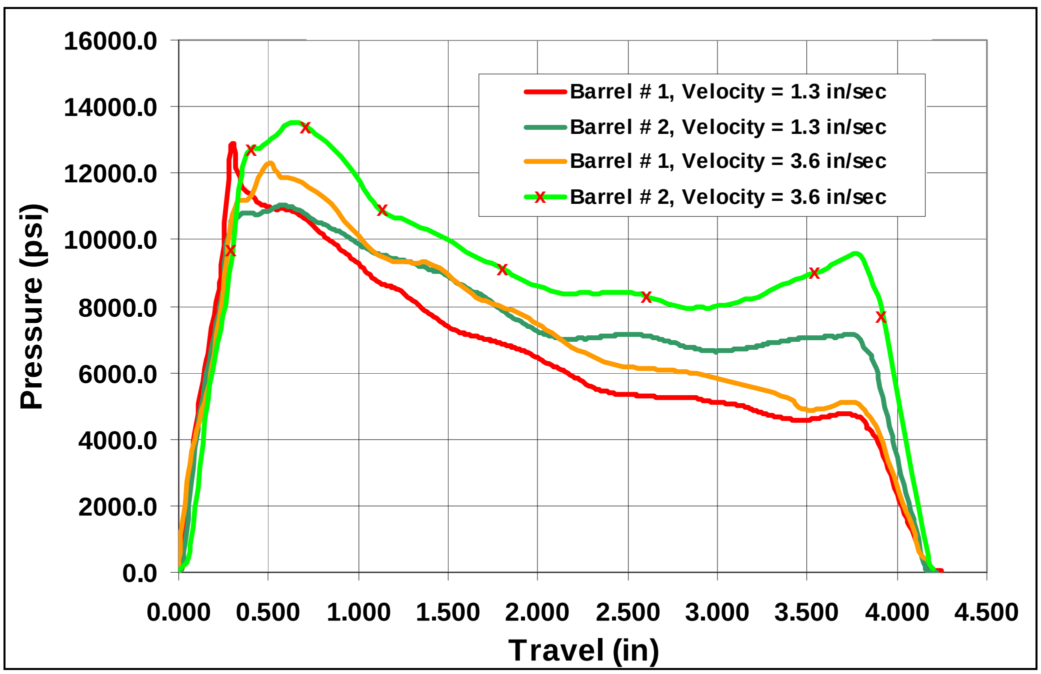

Figure 11. M855 average engraving pressure by barrel and testing rate.

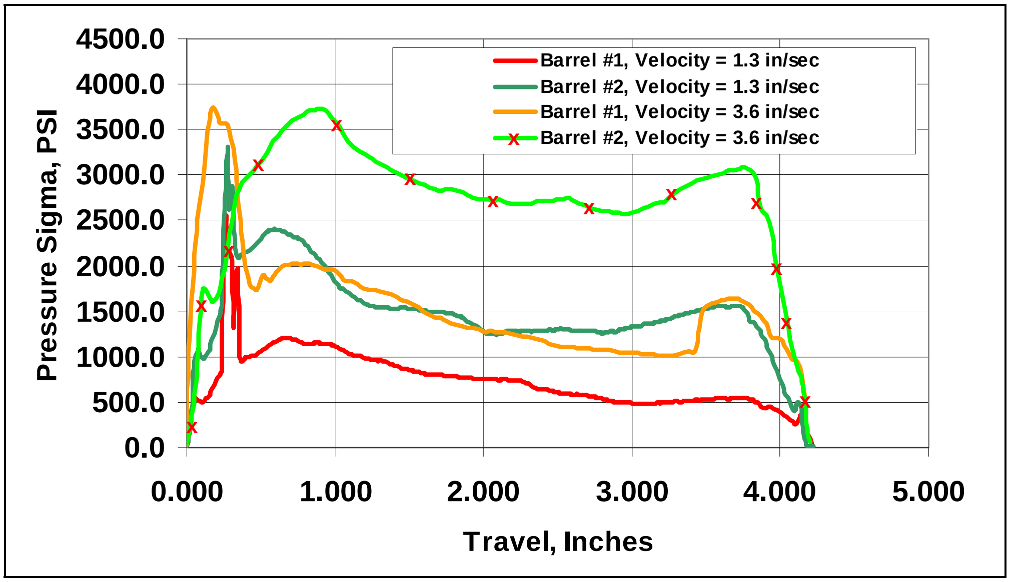

Figure 12. M855 engraving pressure standard deviation vs. travel, barrel and testing rate.

An increase in the standard deviation of the engraving pressure near the end of the forcing cone is expected due to variability in the engraved length of the projectile. Some projectiles exhibit large engraving pressure values while others have very low push force values. The engraving pressure standard deviation as a percent of the mean measured engraving pressure is shown in figure 13. Figure 13 shows wide variability in engraving pressure standard deviation at either end of the engraving pressure travel for two reasons. Early in the in-bore travel, the push force is quite low, so small differences in engraving pressure result in large percent pressure for standard deviations. At the end of travel, the reason for increased variability has already been discussed.

In prior projects involving push testing of the 7.62-mm M80 projectile, the tested results generally exhibited an increase in peak engraving pressure with increasing number of projectiles pushed through the barrel (*2*). This trend was generally not observed with the 5.56-mm M855 projectile pushed through the M16A2 barrel sections, as shown in figure 14. It is believed the improved peak push for consistency of the 5.56-mm test compared to the 7.62-mm test is due to two factors. First, the barrel sections were scrubbed with copper solvent in between shots, which tends to remove any copper deposits left behind in the bore of the barrel section due to friction between the projectile jacket and the bore. Second, the push rod for the 5.56-mm testing was a very close diameter match to the bore lands. This near diameter match reduced the tendency for the projectile material to shear past the punch during the engraving process. Jacket material that sheared between the punch and the rifling would deposit on the lands and result in an increase in the peak engraving pressure with increasing number of projectiles pushed.

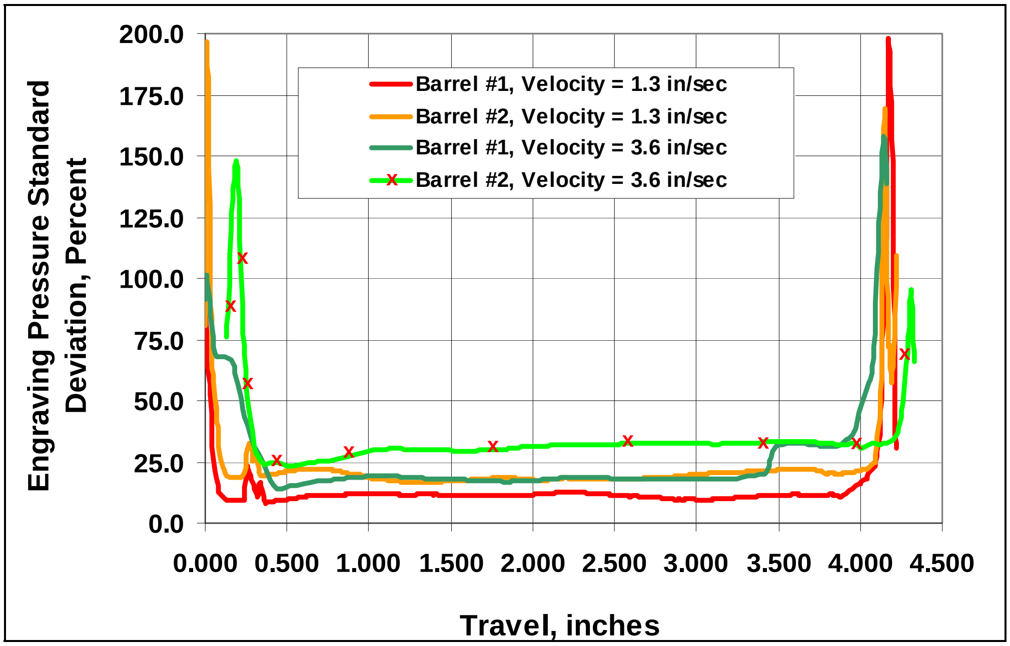

Figure 13. M855 engraving pressure standard deviations as a percentage of average engraving pressure vs. travel, barrel and testing rate.

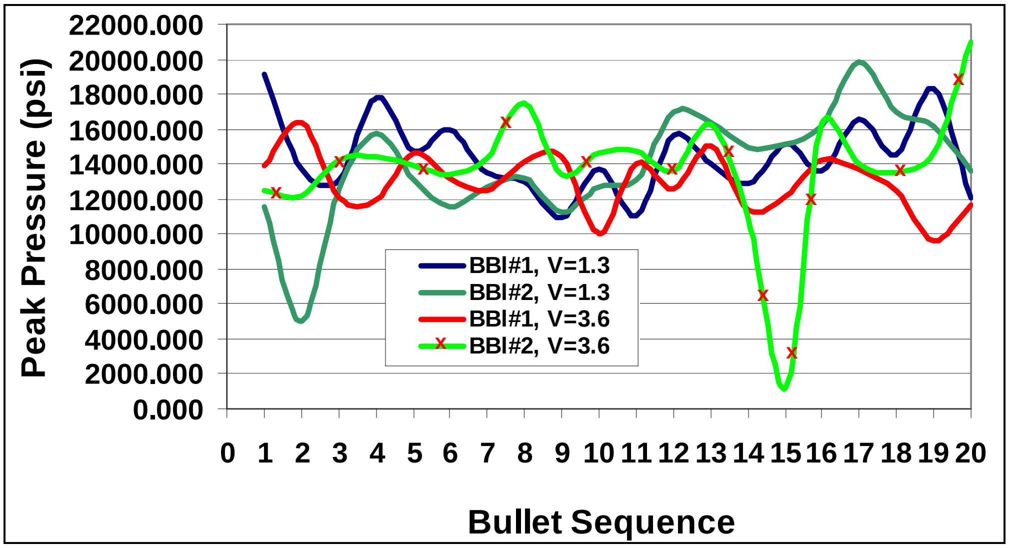

Figure 14. Peak engraving pressure vs. the number of projectiles tested for both M16A2 barrels at both testing rates.

4. Interior Ballistic Simulations

Variability in projectile engraving resistance can have a dramatic effect on the peak pressure generated by the propellant. However, variability in peak pressure does not necessarily translate directly or linearly into muzzle velocity variability. Table 1 lists the mean engraving pressure vs. travel for the M855 projectile in the M16A2 barrel, along with the mean ±2 σ of the engraving pressures. Figure 15 graphically depicts the data presented in table 1.

Table 1. Tabulated M855 mean and ±2 σ engraving pressures.

Travel (in)	M855 Mean Engraving Pressure (psi)	Mean +2 σ Engraving Pressure (psi)	Mean –2 σ Engraving Pressure (psi)
0.00	2142	2181	2103
0.13	2142	5097	-813
0.15	6000	9438	2562
0.25	8700	11618	5782
0.30	11000	13954	8046
0.66	11000	16259	5741
1.00	10000	13972	6028
1.25	9300	13176	5424
1.50	8778	12504	5052
2.00	7500	10793	4207
2.50	6500	10071	2929
3.00	6200	7822	4578
3.50	6000	7622	4378
4.00	5800	7422	4178
4.45	5500	7122	3878
8.77	5000	6622	3378
13.09	3000	4622	1378
17.42	2500	4122	878

Early in the interior ballistic cycle, the rate of volume generation as a result of projectile travel strongly influences the peak chamber pressure achieved by a cartridge. To this end, projectile/barrel/forcing cone combinations that exhibit increased resistance to initial projectile movement also exhibit increased peak chamber pressure. Using the engraving pressures listed in table 1 and conducting a numerical integration simulation of the interior ballistics cycle of the M855 using PRODAS 2000 (*7*), it is possible to estimate the effect on interior ballistic performance caused by engraving pressure variability.

By simulation, the effect on interior ballistic performance of varying resistance pressure is listed in table 2. Figure 16 shows the effect of barrel and forcing cone configuration on the expected peak pressure for uncoated M855 projectiles in each of the test barrels.

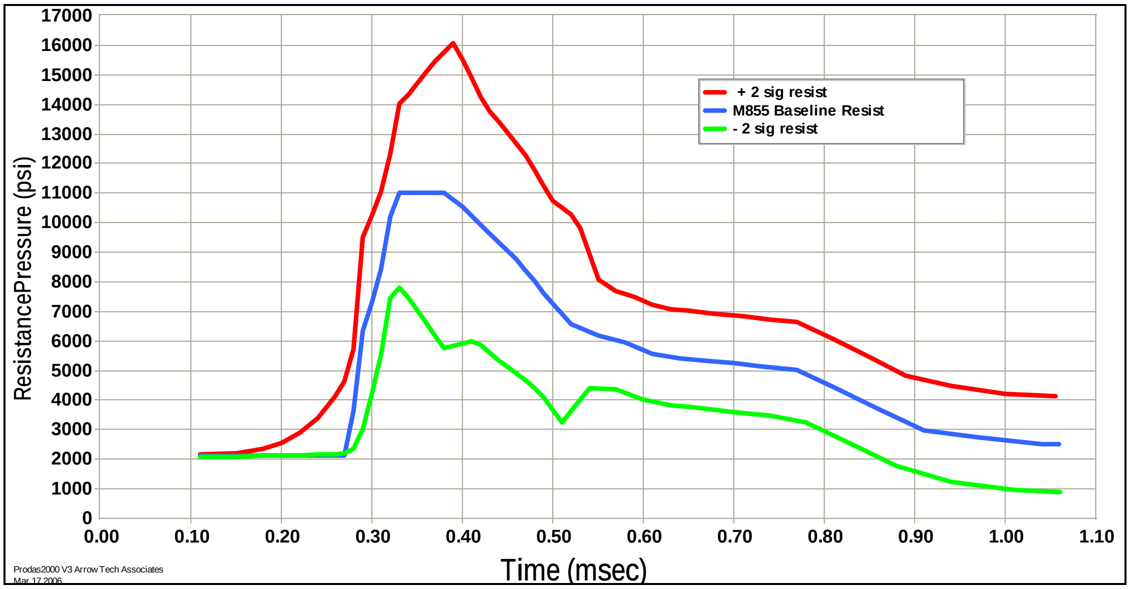

Figure 15. Chamber and resistance pressure vs. time for M855 projectiles.

Table 2. Effect of resistance pressure variations on simulated peak pressure, muzzle velocity, and action time.

Condition	Peak Pressure (psi)	Muzzle Velocity (fps)	Action Time (ms)
Mean	56020	3077	1.060
Mean +2 σ	62076	3101	1.055
Mean –2 σ	51768	3061	1.061
Sigma value	~2560	~10	~0.0015

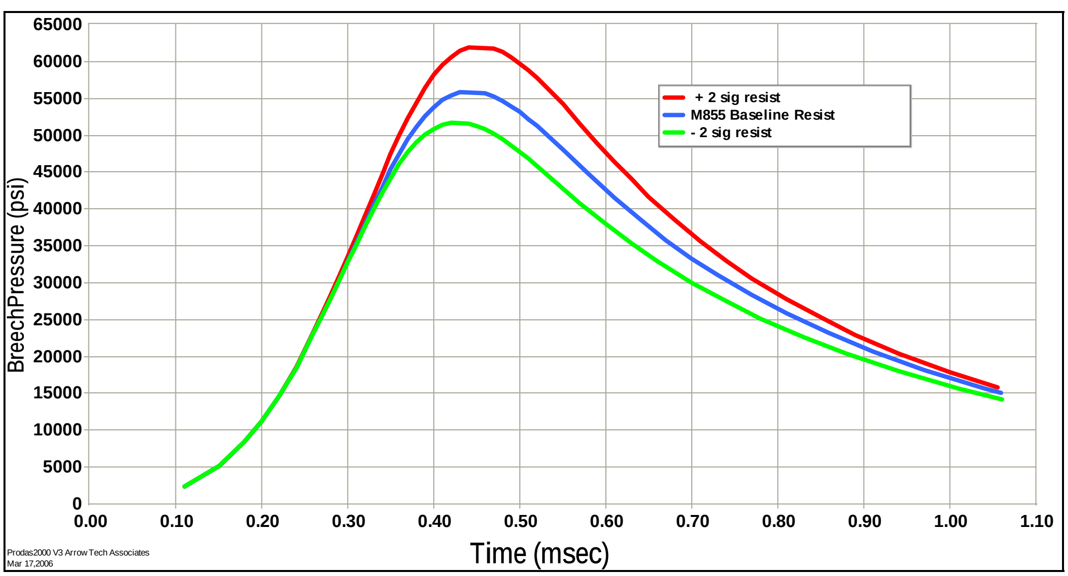

Figure 16. Predicted pressure vs. time for M855 bullets with varying resistance pressures.

In 2004, Arrow Tech Associates provided structural analytical support to Alliant Techsystems for a contract to provide 5.56-mm aluminum-cased cartridges to ARDEC (*8*). In that work, a characterization of the M855 cartridge with a brass case yielded the performance shown in table 3.

Table 3. Observed M855 cartridge means and standard deviations.

Condition	**Peak Pressure (psi)**	**Muzzle Velocity (fps)**
Mean	55079	2936*
Sigma value	~1080	~20

Comparing the estimated sigmas in pressure and velocity between table 2 and table 3, it is seen that the peak pressure variability as assessed by the interior ballistic simulation is considerably larger than that observed in actual firings. This could be caused by several factors, among them are:

- The interior ballistics model does not accurately simulate the state of propellant combustion.
- The resistance pressure in the "real world" may be reduced by the barrel expansion caused by internal pressurization of the barrel prior to peak pressure.
- Heat and gas wash accompanying actual firing removes a different amount of deposited jacket material than does hand cleaning with bore solvent.

Figure 17 shows the effect of varying engraving pressure on simulated pressure-travel history for the M855.

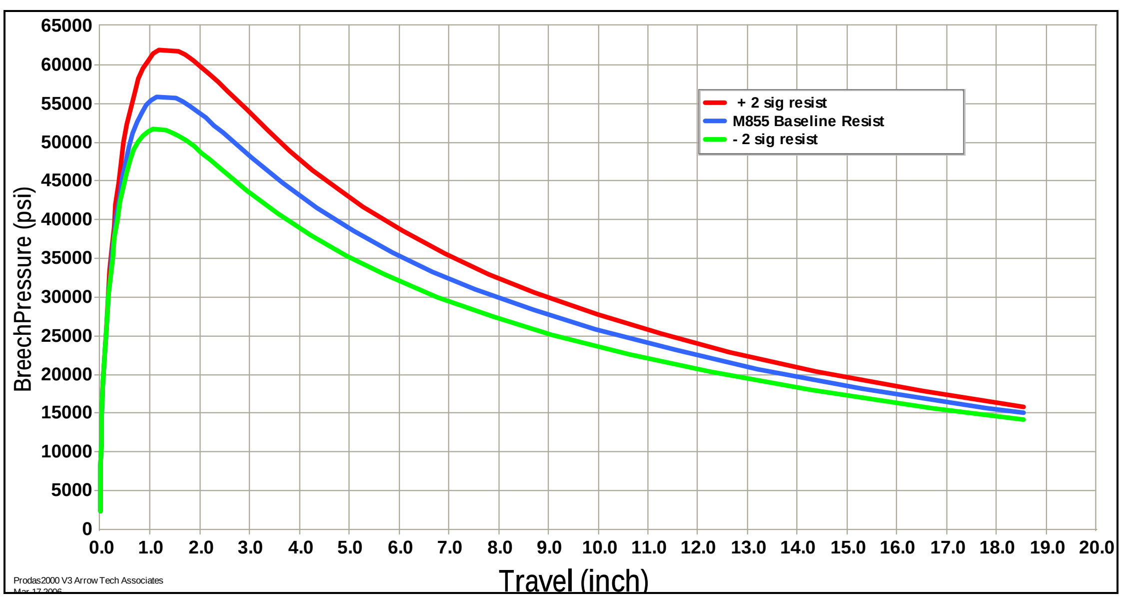

Figure 17. Predicted pressure vs. travel for M855 bullets with varying engraving pressures.

Figure 18 shows the resulting effect on the predicted velocity vs. travel for varying engraving pressures.

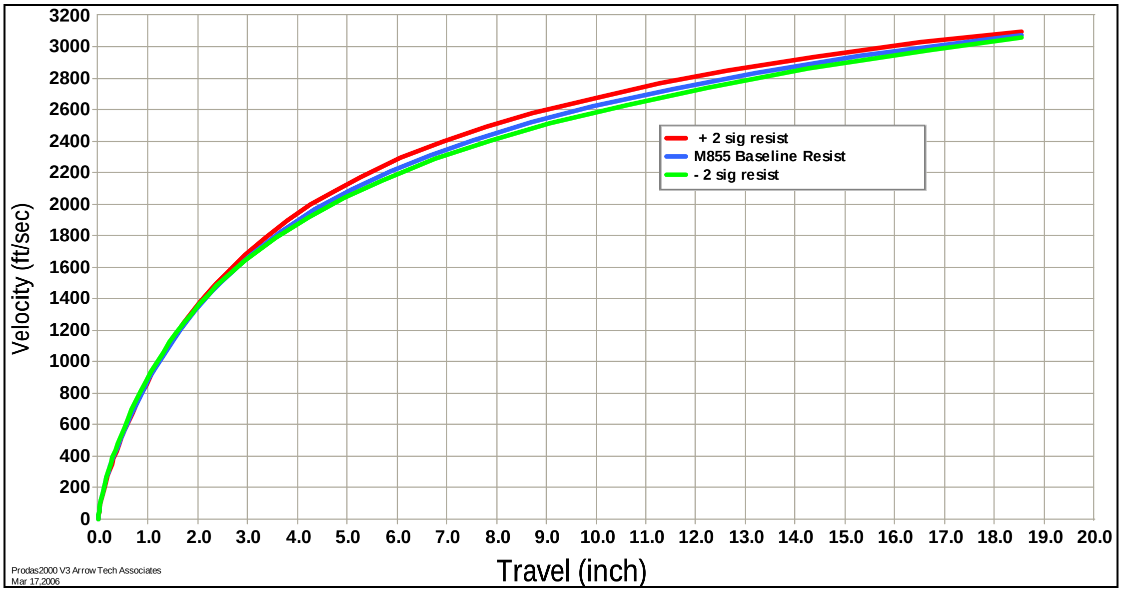

Figure 18. Predicted velocity vs. travel with varying resistance pressures.

The differences in boundary conditions between push test and real world firings may help explain the "disconnect" seen between varying the engraving force and the resulting effect on peak pressure and muzzle velocity. The differences between the boundary conditions of the push test vs. "real world" firings are:

- Push load on aft end of projectile vs. pressure load,
- No barrel expansion present as a result of internal barrel pressurization (function of pressure distribution along sealing surface between projectile and barrel),
- No projectile acceleration or concomitant projectile body deflections, and
- Low rate, constant speed engraving vs. high rate, accelerating velocity engraving.

5. Small-Caliber Resistance Pressure Algorithm

With the engraving pressure data gathered for the M855 projectile in 5.56 mm, and the previously collected data from 7.62-mm testing (*9*), it is possible to construct a predictive algorithm to estimate the engraving pressure of small caliber projectiles. The algorithm incorporates the following projectile characteristics:

- Projectile construction: jacketed or solid,
- Projectile material properties: elastic modulus,
- Projectile dimensions: outside diameter, internal geometry, core length, engraved length, and
- Projectile external lubrication: yes or no.

The algorithm also accounts for the effects of the barrel interface on the engraving process. The gun barrel parameters the algorithms uses are:

- Land diameter,
- Groove diameter,
- Groove-to-land width ratio,
- Projectile free run, and
- Forcing cone half angle.

A pressure is computed for each bourrelet according to the algorithm shown in table 4.

$$P = \frac{\left(GIF * {}^{G}\!/\!{}_{L}\, Ratio + LIF\right)^{0.1772} * RSF * \left(Eng.Length\right)^{3.84} * \left(ScaleFactor\right)^{-0.5922} * LF}{\left(\tan FCHalfAngle\right)^{0.3095}}, \qquad (1)$$

where:

GIF	= Groove interference factor (calibers),
G/L Ratio	= Groove-to-land width ratio,
LIF	= Land interference factor (calibers),
RSF	= Radial stiffness factor (a scalar between 0.05 and 1.29 computed via algorithm which considers wall thickness and elastic modulus, normalized to steel components),
Eng. Length	= Engraved length of the projectile, calibers,
Scale Factor	= (Groove diameter, mm × G/L Ratio + land diameter, mm),
LF	= Lubrication factor; 1.0 if unlubricated, 0.20 if lubricated, and
Tan FC Half Angle	= Tangent of forcing cone half angle.

The pressure generated by equation 1 is then multiplied by a “reference pressure” listed in table 4 along with the travel shown in the left-hand column.

Table 4. Normalized resistance pressure table.

Calibers	REF PSI	REF MPA
0	2030.00	14.00
“Free run + 0.25 Cal”	5816.40	40.11
“1.35 Calibers”	8214.98	56.66
Band L + FC Len+ Cal * 1.35	8214.98	56.66
4	8182.30	56.43
5	7306.51	50.39
6	6720.99	46.35
7	6425.74	44.32
8	5844.10	40.30
9	5259.69	36.27
10	4675.28	32.24
12.5	=Prev. Value - 5%	=Prev. Value - 5%
15	=Prev. Value - 5%	=Prev. Value - 5%
20	=Prev. Value - 5%	=Prev. Value - 5%
25	=Prev. Value - 5%	=Prev. Value - 5%
30	=Prev. Value - 5%	=Prev. Value - 5%
35	=Prev. Value - 5%	=Prev. Value - 5%
40	=Prev. Value - 5%	=Prev. Value - 5%
50	=Prev. Value - 5%	=Prev. Value - 5%
75	=Prev. Value - 5%	=Prev. Value - 5%
200	=Prev. Value - 5%	=Prev. Value - 5%

In the case of projectiles with dramatically different construction between the aft bourrelet and the forward bourrelet (e.g., M903 50-Cal SLAP [*10*]), a weighted average of the resistance pressure at each bourrelet is used to compute the engraving pressure. Figure 19 shows a comparison of the measured and predicted engraving pressure for the 5.56-mm M855 projectile, along with the 7.62-mm M80 projectile and a Barnes 150-gr solid copper projectile.

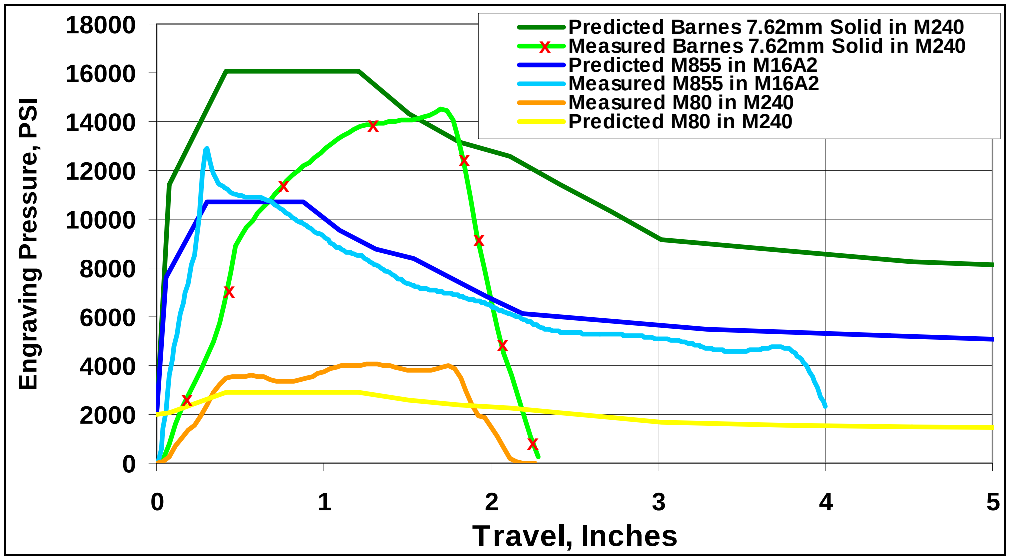

Figure 19. Comparison of small caliber measured and predicted engraving pressure.

The 7.62-mm data shown in figure 19 terminates at about 2.2 in of travel, a limit imposed by column buckling considerations of the punch used to conduct the test.

The small caliber engraving pressure algorithm will be provided in spreadsheet form under separate cover.

6. Conclusions

1. The engraving pressure of the M855 projectile has been measured on 20 samples in two different M16A2 barrels at 1.3 and 3.6 in/s. The average peak engraving pressure is ~12000 psi (~83 MPa).
2. The standard deviation in engraving pressure is about 20% of the measured pressure. When the observed variability (standard deviation) in projectile engraving force is used in a lumped parameter interior ballistics code, the effect on peak pressure variability is over predicted, while the effect on muzzle velocity standard deviation is under predicted. Factors relating to bore expansion, bore surface cleanliness shot-to-shot or modeling of propellant deterrent may be responsible for the lack of correlation between peak pressure and muzzle velocity standard deviations predicted by the interior ballistics model and the sigmas observed in the real world.
3. Projectile construction and elastic modulus of the jacket and core play significant roles in the engraving pressure of small-caliber projectiles.

7. Recommendations

1. Longer barrel sections could be used for future testing to ensure accurate recording of the engraving pressure decay.
2. For future testing, the sample size should be increased (up to 50 or so) until a steady-state push force is achieved. Given the relative rapidity with which the data can be accumulated, this should not be a large cost driver.
3. Alternate barrel cross sections (e.g., G/L ratio, L&G diameters, forcing cone angle, etc.) should be fabricated to determine the sensitivity of the engraving pressure to small variations in these barrel interface parameters.

4. Alternate projectile "as made" dimensions should be included in test samples for any future testing to determine the sensitivity of the engraving pressure to small variations in these projectile interface parameters.

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